Overexpression of the Na-K-ATPase α2-subunit improves lung liquid clearance during ventilation-induced lung injury

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Overexpression of the Na-K-ATPase α2-subunit improves lung liquid clearance during ventilation-induced lung injury. Am J Physiol Lung Cell Mol Physiol 294: L1233–L1237, 2008. First published April 18, 2008; doi:10.1152/ajplung.00076.2007.—Mechanical ventilation with high tidal volumes (HVT) impairs lung liquid clearance (LLC) and downregulates alveolar epithelial Na-K-ATPase. We have previously reported that the Na-K-ATPase α2-subunit contributes to LLC in normal rat lungs. Here we tested whether overexpression of Na-K-ATPase α2-subunit in the alveolar epithelium would increase clearance in a HVT model of lung injury. We infected rat lungs with a replication-incompetent adenovirus that expresses Na-K-ATPase α2-subunit gene (Adα2) 7 days before HVT mechanical ventilation. HVT ventilation decreased LLC by ~50% in untreated, sham, and Adnull-infected rats. Overexpression of Na-K-ATPase α2-subunit prevented the decrease in clearance caused by HVT and was associated with significant increases in Na-K-ATPase α2 protein abundance and activity in peripheral lung basolateral membrane fractions. Ouabain at 10−5 M, a concentration that inhibits the α2 but not the Na-K-ATPase α1, decreased LLC in Adα2-infected rats to the same level as sham and Adnull-infected lungs, suggesting that the increased clearance in Adα2 lungs was due to Na-K-ATPase α2 expression and activity. In summary, we provide evidence that augmentation of the Na-K-ATPase α2-subunit, via gene transfer, may accelerate LLC in the injured lung.

Acute respiratory distress syndrome; acute lung injury; experimental models; gene therapy

CLEARANCE OF PULMONARY EDEMA OCCURS VIA VECTORIAL Na+ transport where water follows the Na+ gradients isotonically. Na+ enters the alveolar epithelial cells mainly via apical amiloride-sensitive sodium channels and is extracted by the basolaterally located Na-K-ATPases (3, 8, 20, 21, 27, 30, 31). The Na-K-ATPase is a heteromeric enzyme composed of an α- and β-subunit. The α-subunit is the catalytic component of the enzyme containing the binding site for ATP as well as the receptor site for cardiac glycosides (22, 26). Four α-isofoms have been identified, each with a unique tissue distribution (28). The Na-K-ATPase α1- and α2-subunits have been reported in lung (25, 29). The smaller β-subunit is a glycosylated transmembrane molecule that controls α-/β-assemblies and insertion of the Na-K-ATPase into the plasma membrane (29, 31).

In human lungs, the alveolar surface area available for fluid reabsorption and gas exchange is ~100 m2 and is composed of alveolar epithelial type I (ATI) and type II (ATII) cells (7). ATII cells cover 2–5%, whereas ATI cells cover ~95% of the surface area (7). Previous studies have shown that ATI cells are the main site for active sodium transport where ATI cells lack the Na-K-ATPase and serve as a barrier with no part in fluid clearance (13). However, recent reports demonstrated that ATI cells express the Na-K-ATPase α1-, α2-, and β1-isofoms and epithelial sodium channels (4, 15, 24), and, more importantly, ATI cells have a significant role in lung liquid clearance. Ridge et al. (24) reported that the Na-K-ATPase α2-subunit is responsible for ~60% of basal lung liquid clearance, and ~80% of the catecholamine-mediated increase in clearance occurs via upregulation of the Na-K-ATPase α2 in ATI cells.

Mechanical ventilation is used in the care of patients with acute respiratory failure; however, ventilation with high tidal volumes (HVT) may have deleterious effects and cause lung injury (1, 6, 32). It has been demonstrated that mechanical ventilation with HVT increases microvascular filtration coefficient in isolated lungs, produces pulmonary edema in intact animals, and also decreases alveolar epithelial Na+ transport, thus impairing lung liquid clearance (1, 9, 32, 33).

Recently, we have demonstrated that adenoviral-mediated gene transfer results in overexpression of Na-K-ATPase subunits in the alveolar epithelium (12). Overexpression of the Na-K-ATPase α2-subunit was associated with a ~250% increase in lung liquid clearance (LLC) in normal rats (24), and a recent study suggests that Na-K-ATPase β1-subunit gene overexpression in the alveolar epithelium increases Na-K-ATPase function and LLC in a model of HVT (10). Therefore, we hypothesized that Na-K-ATPase α2-subunit (which is normally expressed in ATI cells) overexpression in the alveolar epithelium could positively affect LLC during HVT-induced lung injury in rats. To test this hypothesis, we infected rat lungs with a replication-incompetent adenovirus that expresses a rat Na-K-ATPase α2-subunit gene (Adα2) compared with sham and Adnull-infected controls 7 days before HVT mechanical ventilation and measurement of LLC.

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**METHODS**

**Adenovirus delivery.** Replication-incompetent (E1a−/E3−) human type 5 adenoviruses containing expression cassettes with a human immediate/early CMV promoter/enhancer and a rat Na-K-ATPase α₂-subunit cDNA (Adα₂) or no cDNA (AdNull) were constructed, propagated, purified, and titered as previously described (10). The use of animals for this study was approved by the Northwestern University Institutional Animal Care and Use Committee, according to the NIH guidelines. All animals were provided food and water ad libitum and were maintained on a 12:12-h light-dark cycle. Rats were anesthetized with 40 mg/kg pentobarbital intraperitoneally and orally intubated with a 14-g plastic catheter before adenoviral infection (24). Three experimental groups were studied: sham-surfactant, AdNull, and Adα₂. A mixture of adenovirus in a 50% surfactant/50% dialysis buffer vehicle was administered in four aliquots of 200 μl. Rats were rotated 90° between instillations given at 5-min intervals. Immediately before instillation, a forced exhalation was achieved by circumferential compression of the thorax. Compression was relinquished after endotracheal instillation of 200 μl of virus/vehicle followed by 800 μl of air. Rats were allowed to recover before exhalation. Infected animals were maintained in separate isolator cages for 7 days before conducting experimental protocols.

**HV₇ mechanical ventilation.** Rats were anesthetized with pentobarbital (50 mg/kg ip), trachetomized, and ventilated for 40 min with a HV₇ of 40 ml/kg (maximum peak airway pressures <35 cmH₂O) and a respiratory rate of 50 breathes/min compared with nonventilated controls.

**Measurement of LLC.** The isolated, fluid-filled, perfused lung preparation was performed immediately following HV₇ ventilation as previously described (1, 2, 10, 16). Changes in concentration of Evans blue-tagged albumin instilled into the air space were used to estimate the volume of fluid removed from the alveolar air space. The total unidirectional flux of Na⁺ from the alveolar space (i.e., active transport and passive movement) was calculated from the rate of loss of ³²Na⁺ from the air spaces. Passive Na⁺ flux was calculated by subtracting the active Na⁺ flux (calculated from the rate of net fluid clearance) from total Na⁺ flux (27). Similarly, the flux of mannitol was calculated from the rate of loss of [¹⁴C]mannitol from the air spaces (27). Albumin flux from the pulmonary circulation into the alveolar space was determined from the fraction of FITC-labeled albumin, placed in the perfusate that appeared in the alveolar instillate during the experimental protocol.

**Experimental protocols.** Six experimental groups of rats were used in this study: nonventilated/noninfected (n = 6), Adα₂-infected nonventilated (n = 6), noninfected HV₇ (n = 6), Adα₂-infected + HV₇ (n = 6), AdNull + HV₇ (n = 4), and sham + HV₇ (n = 4). LLC was measured for two consecutive hours. In the first hour, LLC was measured in nonventilated/ventilated rats and infected/noninfected rats to assess the effect of the major intervention on edema clearance. In the second hour, ouabain (10⁻⁵ M) was administered via the vascular perfusate to evaluate the role of Na-K-ATPase α₂-subunit. LLC is expressed as percentage of the instillate volume.

**Isolation and culture of alveolar epithelial cells.** ATII cells were isolated from pathogen-free male Sprague-Dawley rats (200–225 g) as previously described. Briefly, the lungs were perfused via the pulmonary artery, air dried, and digested with elastase (0.1 U/ml). ATII cells were purified by differential adherence to IgG-pretreated dishes, and cell viability was assayed by trypan blue exclusion (>95%).

Cells were suspended in DMEM containing 10% FBS with 2 mM L-glutamine, 40 μg/ml gentamicin, 100 U/ml penicillin, and 100 μg/ml streptomycin and placed in culture for 7 days before the start of all experimental conditions. Cells were incubated in a humidified atmosphere of 5% CO₂/95% air at 37°C.

**Basolateral cell membrane isolation and Western blot analysis.** Approximately two millimeters of peripheral lung tissue were collected from each lobe and homogenized to obtain whole cell lysates and basolateral membranes (BLM) as previously described (12, 17). Briefly, cell lysates were prepared by addition of lysis buffer (20 mM Tris, pH 7.5, 150 mM NaCl, 1 mM EDTA, 1 mM EGTA, 1% Triton X-100, 2.5 mM sodium pyrophosphate, 1 mM Na₃VO₄, 1 μg/ml leupeptin, 1 mM PMSF) and centrifuged at 14,000 g to eliminate the insoluble material. BLM were prepared using Percoll gradient centrifugation as previously described (12, 17). Peripheral lung tissue was homogenized in a buffer containing 300 mM mannitol in 12 mM Tris-HEPES, pH 7.6, and protease inhibitors as described above and centrifuged twice to discard the nuclear and mitochondrial pellet. Supernatant was centrifuged at 48,000 g for 30 min, and the BLM fraction was recovered after the membrane pellet was centrifuged in a 16% Percoll gradient at 48,000 g for 30 min. An equal amount of proteins from cell lysates or BLMs was resolved by 10% SDS-PAGE and analyzed by immunoblotting with specific monoclonal anti-rat Na-K-ATPase α₂ (McB2, generous gift of K. Sweadner, Harvard University). The density of the bands was quantified and normalized to sham-infected controls.

**Na-K-ATPase activity.** Na-K-ATPase activity was determined by [³²P]ATP hydrolysis as described before (18, 24). Briefly, ATII cells were placed on ice, and aliquots (~10 μg protein) were transferred to the Na-K-ATPase assay medium (final volume 100 μl) containing in mM: 50 NaCl, 5 KCl, 10 MgCl₂, 1 EGTA, 50 Tris-HCl, 7 Na₂ATP, and [γ-³²P]ATP (specific activity 3,000 Ci/mmol) in trace amounts (3.3 nCi/μl). The samples were then incubated at 37°C for 30 min, and the reaction was terminated by addition of 700 μl of TCA/charcoal (5%/10% wt/vol) suspension and rapid cooling to 4°C. After separating the charcoal phase (12,000 g for 5 min) containing the unhydrolyzed nucleotide, the liberated ³²P was counted in an aliquot (200 μl) from the supernatant. Na-K-ATPase activity was calculated as the difference between test samples (total ATPase activity) and samples assayed in the same medium, but devoid of Na⁺ and K⁺ and in the presence of 4 mM ouabain (ouabain-insensitive ATPase activity) (18, 24). Results are expressed as mean nmol Pi/mg protein/hour of triplicate measurements from three animals per group.

**Statistical analysis.** Data are presented as mean values ± SD. One-way analysis of variance was used when multiple comparisons were made. Differences among groups were considered significant when P value was <0.05.

**RESULTS**

**LLC.** LLC was increased ~70% in rats infected with Adα₂ compared with control (n = 6), AdNull-infected (n = 4), or sham-infected rats (n = 4) (Fig. 1). In rats ventilated with HV₇,

![Fig. 1. Lung liquid clearance was increased in rat lungs with overexpressed Na-K-ATPase α₂-subunit cDNA (Adα₂) compared with uninfected control (CT) rat lungs. Lung liquid clearance in Adα₂ lungs ventilated with high tidal volume (HV₇) was 3-fold greater than in the other HV₇ groups and similar to nonventilated Adα₂ lungs. Data represent means ± SE. *P < 0.01. n.s., Not significant.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3031810/bin/ajplung2008-131848-gf1.jpg)

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LLC decreased by ~50% in noninfected control (n = 6), sham-infected (n = 4), and Adnull-infected (n = 4) rat lungs compared with nonventilated/noninfected control lungs (n = 6). Overexpression of the Na-K-ATPase α2-subunit restored the lung’s ability to clear edema in rats exposed to HVTV ventilation for 40 min (from 12% to 20.4% per hour) (Fig. 1).

In rodent tissue, it is possible to distinguish physiologically between the Na-K-ATPase α1- and α2-subunits due to the large difference in their affinity for ouabain. The Na-K-ATPase α2-subunit, but not the Na-K-ATPase α1-subunit, is inhibited by 10 μM ouabain (24), whereas >1 mM ouabain is needed to inhibit the rat Na-K-ATPase α1-subunit (24). We determined the contribution of the Na-K-ATPase α2-subunit to LLC by perfusing 10 μM ouabain through the pulmonary circulation of the isolated rat lung model. In the presence of 10 μM ouabain, LLC was decreased ~60% in noninfected control, Adnull-, and sham-infected HVTV rats compared with nonventilated/noninfected control rats, suggesting that the Na-K-ATPase α2 is important in LLC (Fig. 2). Importantly, in rat lungs infected with Adα2 and subsequently ventilated with HVTV, ~80% of the increase in LLC was due to the high-affinity ouabain-sensitive Na-K-ATPase α2-subunit (Fig. 2). Alveolar epithelial permeability to small solutes (22Na+ and [3H]mannitol) increased in rats ventilated with HVTV for 40 min compared with noninfected, nonventilated control rats (Fig. 3). Evans blue dye-bound albumin instilled in the air space was not detected in the perfusate or bath compartments in any of the experimental groups. The movement of FITC-albumin from the pulmonary circulation into air space was increased in animals ventilated with HVTV (Fig. 3).

To determine whether the changes in LLC were due to changes in the expression and function of the Na-K-ATPase, we isolated BLM from peripheral lung tissue or ATII cells from HVTV-ventilated and nonventilated rats infected with Adα2, Adnull, or control, noninfected rats. As shown in Figs. 4 and 5, HVTV resulted in a significant decrease in Na-K-ATPase α1, α2, and β1 protein abundance and Na-K-ATPase activity in Adnull and control, noninfected rats compared with nonventilated, Adnull-infected and control, noninfected rats. In contrast, there was an ~57% and 49% increase in Na-K-ATPase α2 protein abundance and Na-K-ATPase activity, respectively, in nonventilated, Adα2-infected rats.

Importantly, Na-K-ATPase α2 protein abundance and Na-K-ATPase activity was maintained in HVTV-ventilated Adα2 rats compared with HVTV-ventilated Adnull-infected rats. These results suggest that overexpression of the Na-K-ATPase α2 protein maintains the Na-K-ATPase activity which then contributes to the restoration of LLC in rats exposed to HVTV ventilation.

**DISCUSSION**

Although mechanical ventilation is a life-saving procedure in patients with acute respiratory failure, it can also induce or worsen acute lung injury (1). Previous studies have shown that ventilation with HVTV can disrupt the alveolo-capillary barrier, which results in leakage of fluid and blood constituents into the alveolar spaces as well release of inflammatory mediators (1, 5, 9, 23, 32, 33). Other reports have demonstrated that mechanical ventilation with HVTV diminishes LLC. These changes were associated with decreased Na-K-ATPase activity in alveolar epithelial cells isolated from HVTV-ventilated lungs (6, 9). Recently, several studies reported that both ATII and ATII cells have a role in active sodium transport and that ATII express both the Na-K-ATPase α1 and the α2 isoforms (4, 16, 24). It has also been suggested that the Na-K-ATPase α2 contributes to the active Na+ transport and LLC, which can be further increased by stimulation of the β-adrenergic receptor or by adenovirus-mediated overexpression of the Na-K-ATPase α2-subunit in noninjured, normal rat lungs (24).

In basal conditions, the Na-K-ATPase α1 is working at ~20–50% of its maximum capacity, whereas the Na-K-ATPase α2 is working at 1/20th of its Vmax (18). A previous report demon-
Na-K-ATPase α2-SUBUNIT OVER_EXPRESSION

Fig. 4. Representative Western blot for Na-K-ATPase α1- and α2-subunit protein (10 μg/lane) abundance in basolateral membranes isolated from peripheral lungs of rats ventilated with HVT for 40 min. Quantitative densitometric scan of blots are depicted in bar graphs. Data are means ± SD, n = 3. *p < 0.05, **p < 0.001 compared with nonventilated control.

strated that overexpression of the Na-K-ATPase α1 subunit in the rat epithelium did not increase Na-K-ATPase activity or LLC; however, overexpression of the Na-K-ATPase β1-subunit resulted in increased fluid clearance from rat lungs (12). Here, we report that overexpression of the Na-K-ATPase α2, which has been reported to be localized to rat ATI cells (24), plays an important role in LLC in the injured lung. We speculate that is due to the Na-K-ATPase α2-subunit’s large reserve capacity to exchanging Na⁺ and K⁺ compared with the Na-K-ATPase α1-subunit. Since the ATI cells cover more than 95% of the alveolar surface area and express key transport proteins (i.e., Na⁺ channels and Na-K-ATPase), our results support the concept that ATI cells have an active role in LLC. HV₉ causes epithelial cell injury, including ATI cell damage, leading to edema in part due to the decreased ability of ATI cells to respond to the increased need of edema resolution. In patients with adult respiratory distress syndrome, impaired ability of the lung to clear edema was associated with worse outcomes (33), which prompted us to study whether overexpression of the Na-K-ATPase α₂ would upregulate alveolar Na-K-ATPase function and sustain LLC in a HVT model of acute lung injury previously shown to impair alveolar active Na⁺ transport (16).

In the present study, we provide evidence that overexpressing the Na-K-ATPase α₂ significantly increased LLC in a model of HVT ventilation in rats. HVT reduced LLC by ~50% in untreated, sham, and Adnull-infected controls confirming that this HVT model impairs alveolar fluid clearance in rats. Notably, overexpression of Na-K-ATPase α₂-subunit was protective in rats ventilated with HVT as LLC was ~350% higher than in the other HVT groups. Clearance in the Adα₂/HVT lungs was 70% greater than nonventilated, unaffected controls and similar to Adα₂-overexpressing nonventilated lungs (see Fig. 1).

In rodent tissues the Na-K-ATPase α₁- and α₂-subunits can be distinguished by their low and high affinity for ouabain, respectively (22, 25, 26). As shown in Fig. 2, ouabain at 10⁻⁵ M, a concentration that predominantly inhibits the Na-K-ATPase α₂, decreased LLC in Adα₂-infected lungs to the same level as sham and Adnull-infected lungs suggesting that the observed increases in LLC in Adα₂ lungs are due to increased Na-K-ATPase α₂ activity. Western blot analysis of BLMs isolated from the peripheral lung of HVT rats demonstrated that α₂-subunit gene transfer significantly increased the abundance of the α₂-subunit protein, whereas HV₉ significantly decreased the α₁-subunit protein in all rat lungs including HV₉-Adα₂ rats. Also, we observed that α₂-subunit overexpression was associated with a significant increase in Na-K-ATPase activity in BLM fractions isolated from the peripheral lung.

We have previously shown that adenoviral-mediated gene transfer can result in sustained overexpression of Na-K-ATPase in

Fig. 5. Effect of mechanical ventilation on Na-K-ATPase activity. Na-K-ATPase activity decreased in primary alveolar epithelial type II cells isolated from rat lungs infected with either Adnull or Adα₂ and ventilated with HV₉ for 40 min. Bars represent means ± SD.
the lung for at least 10 days in rats, and overexpression of the Na-K-ATPase β1-subunit had beneficial effect in hyperoxic lung injury and restored LLC in the rat models of ventilator-induced lung injury and acute left atrial pressure elevation (1, 2, 10). During acute lung injury reduction of active Na+ transport, absorptive capacity and impairment of alveolar barrier function shifts transalveolar fluid balance toward air space edema accumulation which represents a significant challenge in the treatment of these patients. Adenoviral-mediated gene expression facilitates prolonged transgene expression and reduced host responses (14). High-efficient gene transfer to severely injured patients via the HVT ventilation-injured lung by upregulating LLC. Since the HVT gene transfer increases liquid clearance during ventilation-induced lung injury.

In summary, we provide the first evidence that overexpression of the α2 Na-K-ATPase subunit has a beneficial effect on the HVt ventilation-injured lung by upregulating LLC. Since the α2 Na-K-ATPase is expressed in ATI cells, which cover more than 95% of the alveolar surface area, our results support the notion that ATI cells may have a significant role in LLC, and upregulation of alveolar Na-K-ATPase function, via gene transfer, is of benefit during ventilation-induced lung injury.

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